INVESTIGATION OF THE BAGNOLD DUNES BY THE CURIOSITY ROVER: OVERVIEW OF INITIAL RESULTS FROM THE FIRST STUDY OF AN ACTIVE DUNE FIELD ON ANOTHER PLANET

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Introduction: For much of Mars' history the dominant geomorphic processes have been due to wind. Surface investigations from the MERs and later the Mars Science Laboratory (MSL) Curiosity rover have studied, in situ, ripples, sand shadows, and megaripples/TARs [1-4], but an active dune field on Mars (or any planetary body besides Earth) has, until now, never been visited up close despite the fact that sandstones make up a significant component of the Martian stratigraphic record [5,6]. Gale Crater contains large, active dunes that are accessible for in situ investigation. The rover traverse path passes through the informally-named Bagnold Dunes (Fig. 1), which are actively migrating [7]. Here we review initial results from the campaign at a high level and cite related LPSC abstracts that focus on specific details.

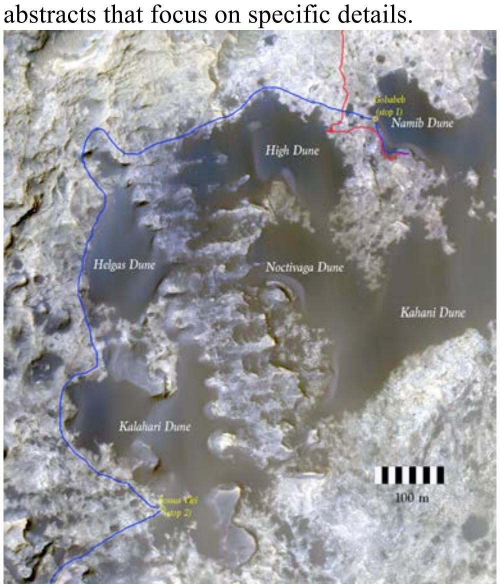

Fig. 1: Curiosity's traverse through the Bagnold Dune field. Red is the ~path taken so far (as of this writing) and blue is the notional route upcoming.

Science Goals and Objectives: The MSL Bagnold dune campaign addresses four broad science goals: 1) Understanding current Martian dune processes and rates, including differences between dunes and other bedforms, 2) deciphering dune processes, rates, and geochemical pathways in the past, 3) constraining dune material provenance, and 4) assessing the dunes as traps for interplanetary dust particles (IDPs) and water.

Campaign: The campaign is organized into six phases. Those completed so far (as of this writing) are: 1) Approaching from the north, reconnaissance Mastcam images were made of the stoss slopes of Namib and High Dunes. 2) Within the dunefield, images of Namib and High Dunes were made to assess dune/ripple morphology. The lowest east stoss edge of High Dune was assessed with APXS, MAHLI, and ChemCam (Fig. 2). A sand patch near High Dune was also investigated and a rover mobility test performed [8]. The rover stopped in front of the Namib Dune slipface for 7 sols of observations, including change detection with coordinated REMS blocks. 3) Eight sols of further monitoring of Namib, from a slightly different location, occurred over the December 2015 holiday period.

Planned to follow the submission of this abstract will be 4) the first of two in-situ stops, "Gobabeb," on the secondary slip face margin of Namib Dune [9,10]. This, and the later Sossus Vlei/Kalahari Dune stop, were picked because they represent compositional and activity endmembers along the rover traverse, with the Namib Dune having stronger olivine signatures, lower dust indices, and larger ripple displacements than Kalahari [10]. The focus of the in situ study is trenching and the scooping of dune material, with two size fractions, <150 µm and 150 µm - 1 mm, delivered to SAM and the former also investigated with CheMin. Other activities include Mastcam, MAHLI, APXS, and ChemCam investigations of the trench and grain-sorted dump piles, change detection imaging, Mastcam photometry, active DAN to assess sub-surface hydrogen, and an investigation to determine the possible presence of nighttime-condensed frost on dune sand at this cold time of year [11]. 5) The rover will then drive in a counterclockwise path along the northwestern part of the dunefield. Following this drive, 6) Curiosity will arrive at the Sossus Vlei stop at the downmwind margin of Kalahari Dune for another in situ study.

Initial Results *Mineralogy and Chemistry* The Gobabeb in situ activities have not yet occurred as of this writing, but other analyses have been performed approaching and within the dunefield. ChemCam passive spectra of Bagnold Dune sands are consistent with the presence of olivine [12]. Curiosity investigated the margin of High Dune (Sol 1184-5), thereby providing the first chemical data on an active dune on Mars. Two APXS spots on the High Dune stoss slope margin, and two others in the engineering test sand patch, show less inferred dust (lower S and Cl), greater Si, and higher Fe/Mn than other "soils" in Gale Crater. ChemCam analyses of more than 300 soils along the Curiosity traverse show that both fine (<500 µm) and coarse (>500 µm) soils have increasing iron and alkali content as the

Bagnold Dunes are approached [13], a trend that may reflect admixtures of local rocks (alkalis + iron) to the fines, but also a contribution of Bagnold-like sand (iron) that increases toward the dunefield.

Grain Size and Texture MAHLI images of sands on the lower east stoss slope of High Dune, imaged on Sol 1184, show medium and coarse sand in ripple forms, and very fine and fine sand (with minor medium sand) in ripple troughs. Most grains are dark gray (many with patches of varied color or texture, suggestive of multiple mineralogies and/or pits and facets), but some are also brick-red/brown, white (maybe pieces of locally-derived vein-fill minerals, which are abundant in the local bedrock), green translucent, yellow, brown (possible olivines), colorless translucent, or vitreous spheres [14]. The Sol 1182 rover mobility test [8], in a sand patch adjacent to High Dune, showed in more detail that the medium and coarse sands are largely confined to ~1-grain-thick surface veneer that is underlain by a bulk body of very fine to fine sand. This underlying finer sand exhibits colors ranging across all shades of gray to brick red, with some yellowish and greenish grains.

Fig. 2: A 4x enlargement of a portion of MAHLI image of the “Barby” target on High Dune (MAHLI image 1184MH0005480010402897C00)

Dynamics HiRISE orbital images show that the Bagnold Dunes migrate on the order of decimeters or more per Earth year, although the motion is sporadic and modulated by seasonal variations in wind intensity. Prior to entering the dune field, wind disruption of dump piles and grain movement was observed over multi-sol time spans, demonstrating that winds are of sufficient strength to mobilize unconsolidated material, either through direct aerodynamic force or via the action of smaller impacting grains [15,16]. Within the dune field, we are, as of this writing, engaged in change detection experiments with Mastcam and the ChemCam RMI camera [17]. Data we have so far, spanning 8 sols from the same location, shows no changes. Nevertheless, with active dunes and surrounding rock showing evidence of significant abrasion, sand movement is clearly occurring.

Dune morphology, structure and stratigraphy Mastcam and RMI images of the stoss sides of Namib, Noctivaga, and especially High Dune (where we’ve approached the closest), show that the “ripples” seen with HiRISE are of fairly constant ~1 m wavelength, with clear stoss slopes, sinuous crests, slip faces, and grain flow and fall features (Fig. 3) [18,19]. Superimposed on these smaller bedforms are more definitive ripples of ~10 cm wavelength, similar to impact dune ripples on Earth [19]. The ~1 m scale features may be fluid drag bedforms that form in an aeolian regime distinct from that on Earth due to the large viscous sub-layer in the low density Martian atmosphere [19].

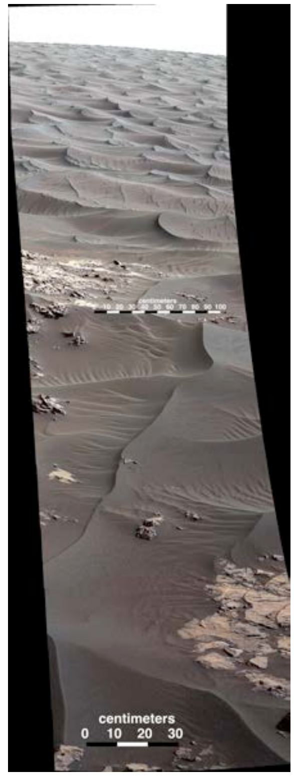

Fig. 3 (left) M100 mosaic of superposed intermediate-scale bedforms and smaller ripples on the surface of High Dune

The slipface of Namib Dune (see Fig. 1 of [18]) shows distinct flow lobes, bounded at the top by alcoves and at the bottom by lobate toes, with prominent detachment scars. Ripples upon and oriented orthogonal to the slipface indicate sand transport from winds within the dune recirculation zone [18]. Some of the flow lobes have few ripples, indicating recent avalanching. The internal structure and stratigraphy of the margin of Namib Dune will likely be forthcoming in the trenching at the Gobabeb stop and will be reported at LPSC.

Summary We have investigated and are investigating, for the first time, an active dune field on another planetary body. With fresh results on grain size, texture, and composition, dynamics, and dune morphology and structures, we have provided critical ground truth data. We expect these results to significantly expand our understanding of current and past aeolian processes, sand provenance, and other questions that heretofore have been addressed solely from remote orbital observations, models, or partial analogs. This campaign will result in significant advancements in Martian and aeolian science.

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